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CLIMATE CHANGE AND VARIABILITY: HOW SHOULD THE DISTRICT RESPOND?

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CLIMATE CHANGE AND VARIABILITY:
HOW SHOULD THE DISTRICT RESPOND?

1. PURPOSE

The South Florida Water Management District (SFWMD or District) has been interested in possible effects of long term climatic variations on the water resources of South Florida for many years. Unfortunately, not much research or planning has been done to date to address these issues. The prevailing attitude has been that a) there is not much that can be done about it, b) the worst problems will occur a long time in the future, and c) efforts need to be focused on more immediate problems.

With the initiation of long range planning efforts (50-years or more), such as the joint Central and Southern Florida Flood Control Project Restudy between the SFWMD and the United States Army Corps of Engineers, it is essential for the District to consider possible future changes that may occur in climate, and to develop strategies that deal with such changes in the design, planning, regulation, and operation of the District's complex water management system.

This paper attempts to identify and assess the potential impacts of both natural variability in climate conditions and changes in Florida's climate that may occur over time, due to natural and human causes, at both local and global scales. A prioritized set of recommendations is also presented. These recommendations are suggested to guide the development of potential District programs that would address key issues related to climate change and variability.

2. CAUSES AND IMPACTS OF CLIMATE CHANGE AND VARIABILITY

2.1. Time Scales of Climate Change and Variability. The concepts of climate change and variability include both short-term and long-term components. The short-term component (generally termed *climate variability*) includes seasonal changes, multiyear extended periods of wet and dry conditions (prolonged periods of above normal hurricane activity, excessive rainfall or drought) and the periodic cyclical changes through wet and dry conditions that occur generally within and 20 year-time frame. Such changes may be related to global events, but have an individual expression and definition at the regional level (e.g. South Florida) that differs from the response in some other region (e.g. Australia).

The long-term component (generally called *climate change*) refers to more or less permanent changes that occur over a longer period and have global implications. The result is an overall trend that has impacts throughout the world. These include phenomena such as increased concentrations of carbon dioxide in the atmosphere, so-called "global warming," impacts of chlorofluorocarbons on the ozone layer and sea level rise.

The District needs to consider the effects of climate variability in planning and making day-today decisions concerning systems operationss, maintenance and activity scheduling. The District also needs to consider climate change for long-term system planning, design and construction, as well as associated needs to protect natural resources, lives, and property.

2.2. Causes of Climate Change and Variability. Both change and variability are occurring simultaneously, so that effects are additive and cumulative over time.

There are many causes of change and the variability of climate in a particular region. Most of these causes can be categorized into two primary groups:

(a) Natural causes such as variability of sunspots, El Nino-Southern Oscillation (ENSO) events, volcanic activity, and others such as the changes in the Atlantic Ocean Conveyor Belt; and

(b) Man-made or Man-Induced, local and global changes. These include changes in water management and land use at the local level, and greenhouse warming, ozone depletion, and other changes occurring at the global level.

A description of the above causes of climate change and variability and the potential impacts are included in **Appendix A**. The time scales, causes and spatial scales of various climate change factors are summarized in Table 1

Table 1. Factors that Influence Climate Change and Variability

Factor Cause/Effect	**Time** (short- vs long-term)	**Source** (Natural vs Manmade	**Spatial Scale** (Local vs Global)
Sun Spots	short	Natural	global
El Nino-Southern Oscillation	short	Natural	global
Volcanic Activity	short	Natural	global
Atlantic Ocean Conveyor Belt	short	Natural	global
Water Management Changes	long	Man-Made	local
Urbanization	long	Man-Made	local
"Greenhouse" warming	long	Man-Made	global
Sea-Level Rise	long	Both (?)	global

2.3 Preliminary Analysis - Factors of Primary Importance to the District. The previous section and the associated appendix discuss numerous factors that can be responsible for short-term and long-term climatic changes and variations in South Florida. Consideration of all these factors, with similar emphasis, is difficult for many reasons. The following should be considered in developing a strategy to address the potential consequences of climatic change on long term water management plans in South Florida:

(a) Currently, the difference between a true change and natural variability cannot be distinguished with certainty. Even if a true change is detected, it may be difficult to attribute the effect to specific causes, since the change itself may derive from multiple sources. Initially the long-term changes may be masked by short-term events and only become apparent in the future, when a sufficiently large or extensive data set has been accumulated over time.

(b) The factors which are more certain than others should be separated from those which are highly uncertain. For example, there is sufficient evidence that sea level rise will continue to occur over the next century or so, although the exact magnitude of the rise cannot be predicted with a reasonable level of accuracy.

(c) Given the global nature of some these changes, it is not practical for the District to invest resources to research them. In these cases, it may be best to monitor the actions of national/international agencies and groups to obtain the state-of-the-art information on these topics of climate change. One such example is global warming due to greenhouse gases.

(d) In some cases, it may be necessary or desirable to collaborate with other agencies, in an effort to address regional and global climate change issues at a local level. This will allow the District to tap the expertise of other agencies and generate their interest to identify and address local problems associated with climate change issues.

3. IMPORTANCE OF CLIMATE CHANGE AND VARIABILITY TO THE DISTRICT

3.1. Long Range Planning, Design, and Regulation. Typically, historical data, which are often only available for the last several decades, have been used as the basis to develop long range water management plans and associated permitting criteria, and to design specific structural features of these plans. For example, in current regional system planning studies, hydrologic conditions during the period 1965-1990 are used as the basis to analyze future scenarios and estimate effects of water management alternatives. Any changes in climate conditions that occur, due to either local or global effects, could cause wetter or drier conditions during the next 50-year planning horizon. The probability that the temporal pattern of the hydrologic process that occurred during the 1965-1990 period will be repeated exactly during the next 50 years is nil. Therefore, plans developed based on this hydrology may be invalid, if hydrologic conditions that actually occur during the next 50 years are radically different from those of the recent past. Examples of key hydrologic parameters that may be influenced by climatic changes include the following:

- rainfall (frequency, magnitude, spatial distribution),
- tropical storms and hurricanes (frequency and magnitude)
- flows (magnitude, seasonality),
- water levels (magnitude, seasonality),
- salinity (concentrations, spatial extent of intrusion), and
- other important climatic variables such as temperature, solar radiation, and humidity.

All these variables play important roles in the current methodologies used at the District for planning, design, and regulation of major water management projects. Any change in their range or natural variability can have a significant impact on success or failure of these projects.

A sensitivity analysis was conducted to determine the effects of 10 percent (greater or lesser) change in rainfall district-wide, over the 1965-1990 period, on the performance measures produced by the South Florida Water Management Model. Results of this analysis, which are documented in **Appendix B**, showed that such a change in rainfall regime could have a significant effect on Lake Okeechobee water levels, estimated economic losses of the Everglades Agricultural area, extreme discharges to estuaries, and the volumes of water supply cutbacks in the Lower East Coast urban area. Such analyses demonstrate the importance of considering possible changes in the future rainfall regime across the District in developing water management strategies to meet water supply and environmental restoration objectives.

Another consequence of climate change is that sea level is projected to rise due to global warming. If the current estimates of sea level rise over the next 100 years (more than one foot) are correct, they can have serious planning implications in terms of urban expansion, issuance of permits, water supply, flood control and environmental restoration. For example, the current criteria for issuing permits for urban development near the coastal belts may have to be revised to account for long term consquences of sea level rise on salt water intrusion, flooding, etc.

3.2 Direct Physical Effects. The ecological and social systems of South Florida have been in a state of adaptive flux since the 1900s. Man's extensive drainage and contstruction activities probably contribute heavily as the underlying sources of many perceived environmental impacts. If a change in climate conditions occurs that results in wetter conditions, many of the current crises may well be replaced by equally bad, reverse conditions. Some possibilities are:

- Hyper-salinity conditions in Florida Bay and other bays and estuaries may be replaced by hypo-salinity problems;
- Invasion of wetlands in the Everglades and other areas by upland vegetation may be replaced by concerns about die-offs of species that are favored under the present regime; and
- The current concerns over lack of water for restoration may be replaced by problems of how to dispose the excess water that accumulates in natural areas, resulting in frequent drowning of deer, destruction of tree islands, increased seepage and water loss to tide etc. etc.

The projections of sea level rise, associated with global climate change, may have the following direct effects:

(a) Inundation of low-lying coastal areas;

(b) Accelerated erosion of shorelines and wetlands;

(c) Accelerated intrusion of saltwater into freshwater aquifers; and

(d) Increased water levels may be needed in canals to control salt water intrusion and may, in turn, cause increased potential for flooding in urban areas.

Many have suggested a possible link between land use changes and the local climate. Such connections, if proven, may also influence the success or failure of future water management efforts. For instance, restoration of major wetlands systems in the Everglades may have a direct influence on the amount of summer time convective rainfall that occurs over South Florida (Pielke et. al, 1988).

3.3 Potential for Improved Operational Forecasting. Climatic events that occur in other parts of the world have been associated with climatic changes and variability in Florida. Some of these "teleconnections" are presently incorporated to help predict weather conditions 10 days or more in advance. With further refinements, it is hoped that such data can be incorporated into a better predictive methodology to forecast short-term and climatic variations in South Florida. For instance, the well known El Nino-Southern Oscillation (ENSO) events also influence climate in South Florida. The ability to predict such an event several months ahead of its occurrence could potentially allow for adjustment of water management strategies to account for anticipated weather changes that may from those ENSO events.

William Gray (1990) has suggested that the seasonal and multidecadal variations of intense hurricane activity are closely linked to seasonal and multidecadal variations of summer rainfall in the Western Sahel region of West

Africa. Based on this relationship, he recently predicted that the apparent breaking of the 18-year Sahel drought during 1988 and 1989 will likely increase the incidence of intense hurricanes that make landfall on the U.S. Coast and in the Caribbean basin. Knowledge of these types of long-range predictions can be extremely useful to help the District make adjustments to operational procedures and emergency preparedness efforts.

4. RECENT CLIMATIC TRENDS IN SOUTH FLORIDA

Several investigations and analyses of historical data sets have shown that changes have occurred in some climatic variables, which suggest gradual or sudden variation in the climatic regime of South Florida. The investigations to date have included the following information:

(a) Rainfall/Runoff across the District;

(b) Sea Level Rise; and

(c) Hurricane Occurrence; and

(d) Predictions from Global Climate Models (GCMs)

4.1 Rainfall/Runoff.

* Several previous investigations at the District indicated that a possible decline in rainfall **(Figure 1)** has occurred since the 1960s (Rhoads et al., 1987; Obeysekera & Loftin, 1990). Although the exact cause of the decrease is not known, many factors have been suggested, including the following: reduction in hurricane strikes; local drainage causing a reduction in thunderstorm generation; natural fluctuations in global climate; and anthropogenic modifications to global climate.

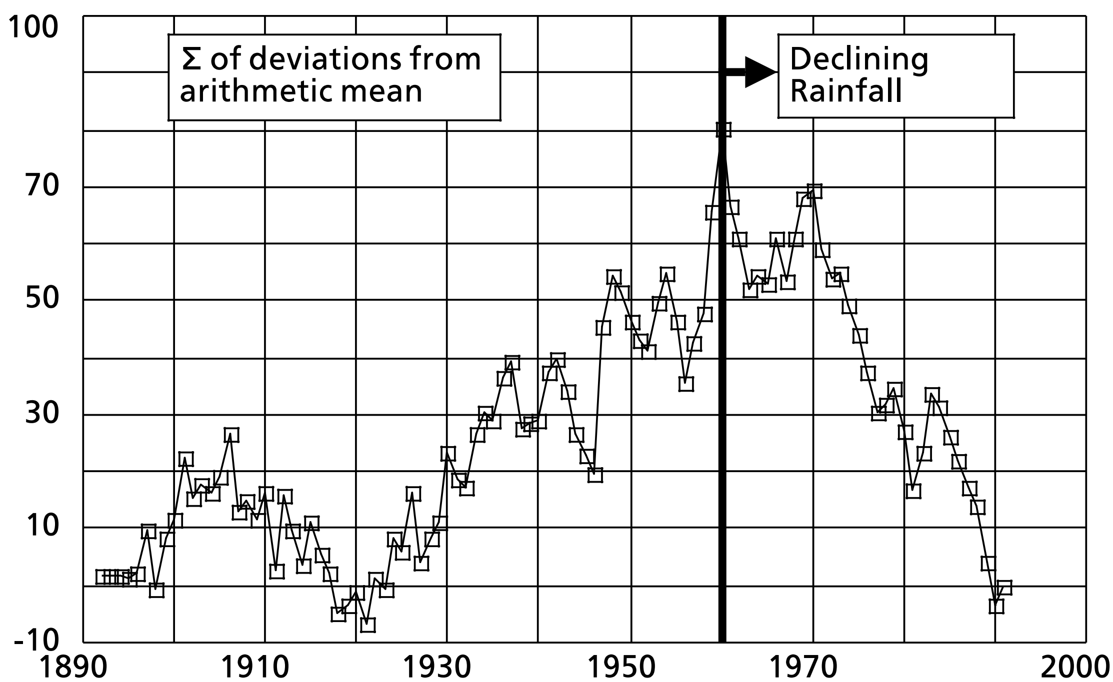

Figure 1. Decline in Rainfall in South Florida Since 1960.Plot of the summation of the annual deviations from measures of central tendency.

* Recent studies (Karl et al., 1996)) suggest that the entire country is experiencing a steady increase in more intensive storm events (extreme 1-day precipitation events that exceed 2 inches) relative to historical occurrences of such events. This increase is particularly apparent between 1910 and 1940 and after about 1970. Scientists have not yet determined whether this trend is also apparent in South Florida .

* Chin (1993) analyzed an extensive data set covering south Florida and concluded that there is some evidence of a downward trend in wet season rainfall. He also demonstrated that there is a significant downward trend in October and April rainfall and possibly an upward trend in November rainfall.

* While investigating options for Kissimmee River restoration, Obeysekera and Loftin (1990) showed that a 10 percent decrease in rainfall in the Upper Kissimmee Basin, combined with land use changes, appears to have reduced the basin runoff by as much as 40 percent. The reduction in corresponding flows in the Kissimmee Basin appears to be larger during the months of October through January **(Figure 2)**.

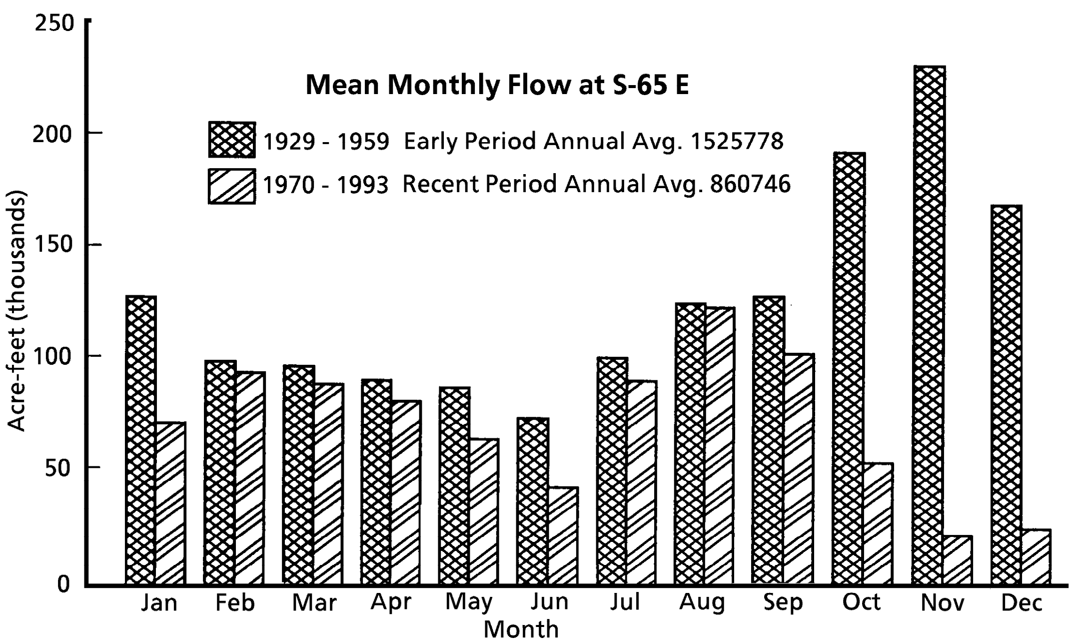

Figure 2. Changes in Flow through the Kissimmee River at S-65 E. Current (1970-1993) relative to historical (1929-1959) Conditions.

* An examination of "wet" and "dry" biennial periods since 1915 reveals a distinctive alternating sequence. When only those two-year periods where rainfall deviated from the historical mean (105") by more than 10% are considered, wet periods (of one or more wet biennial periods in succession) have always been followed by normal rainfall and/or dry periods (of one or more dry biennial periods in succession) and vice versa. The timings of these wet and dry periods appear to be correlated with ENSO phases (El Nino and La Nina). Moderate to strong ENSO conditions occurred at some point in more than 75% of these cases. Six of the seven driest periods were possibly connected to *La Nina* events and the 10 wettest periods were possibly connected to *El Nino* phases. Rankings and coincident tropical activity are included in **Table 2** and **Figure 3.**

Table 2. Relationship between exceptional wet or dry biennial rainfall periods in South Florida and ENSO phases (*El Nino* and *La Nina*) since 1915.

Period	District Biennial Rainfall Using Mean (105") ± 10% *	ENSO	Top 10 Rank Wet/Dry	Tropical Cyclone Highlights
1924-25	Above (116")	La Nina	-/-	2 Storms
1927-28	Below (92")	La Nina	-/9	3 `28 Storms
1929-30	Above (117")	None	-/-	2 Storms
1937-39	Below (93",94")	La Nina	-/10,-	1 Storm
1940-41	Above (116")	El Nino	-/-	2 `41 Storms
1943-45	Below (87",92")	None	-/4,8	2 `45 Storms
1946-48	Above (125",133")	El Nino	7,1/-	6 Storms
1950-51	Below (91")	La Nina	-/6	3 Storms
1953-54	Above (120")	El Nino	10/-	2 `53 Storms
1955-56	Below (84")	La Nina	-/1	None
1957-60	Above (121",129",133")	El Nino	9,4,2/-	4 Storms/2 Yr
1961-62	Below (92")	None	-/7	1 TD
1968-70	Above (128",122")	El Nino	5,8/-	6 Storms
1980-81	Below (89")	None	-/5	1 Storm
1982-83	Above (131")	El Nino	3/-	1 Storm
1988-90	Below (86",86")	La Nina	-/3,2	2 Storms
1993-95	Above (116",127")	El Nino	-,6/-	3 Storms

*__Below__ is less than 105 x.90=94.50"/yr; __Above__=more than 105 x 1.10= 115.50"/yr

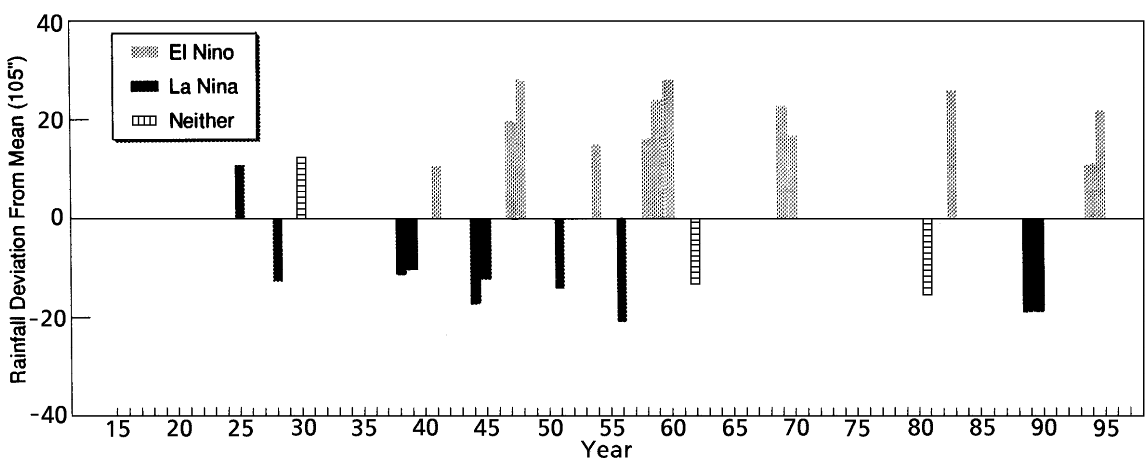

Figure 3. Moderate to Strong El Nino Events Related to South Florida Biennial Rainfall

4.2 Sea Level Rise

* Based on historical data from South Florida, there is a clear indication that sea level is rising **(Figure 4)**. Looking forward in time, the results of the general, global sea-level models clearly support a continuing, more rapid rise in sea level (Rhoads et. al, 1987). What is not clear, however, is the rate at which ocean levels may increase. Forecasts indicate that a median increase in sea-level, up about 500 mm (1.6 feet) could occur during next 100 years **(Figure 5)**.

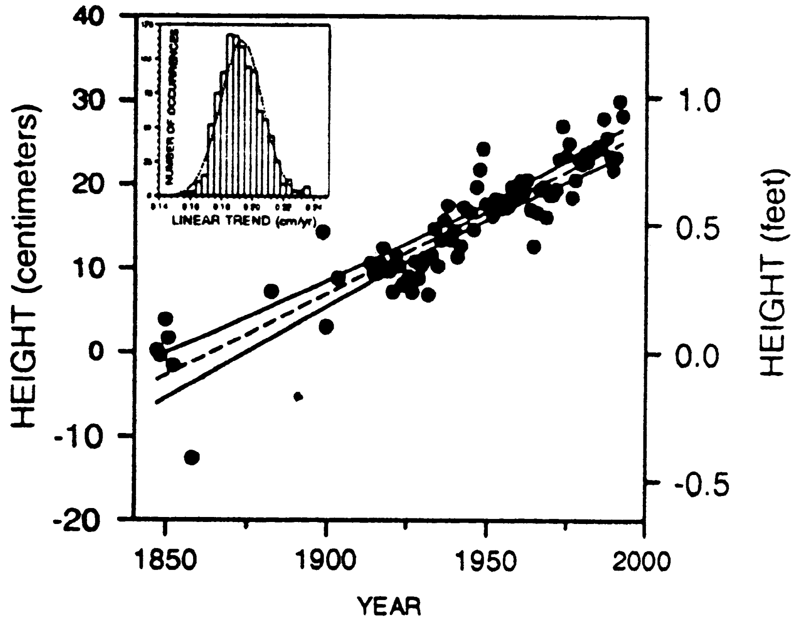

Figure 4. Historical Trends in Sea Level Data at Key West, Florida, since 1850.

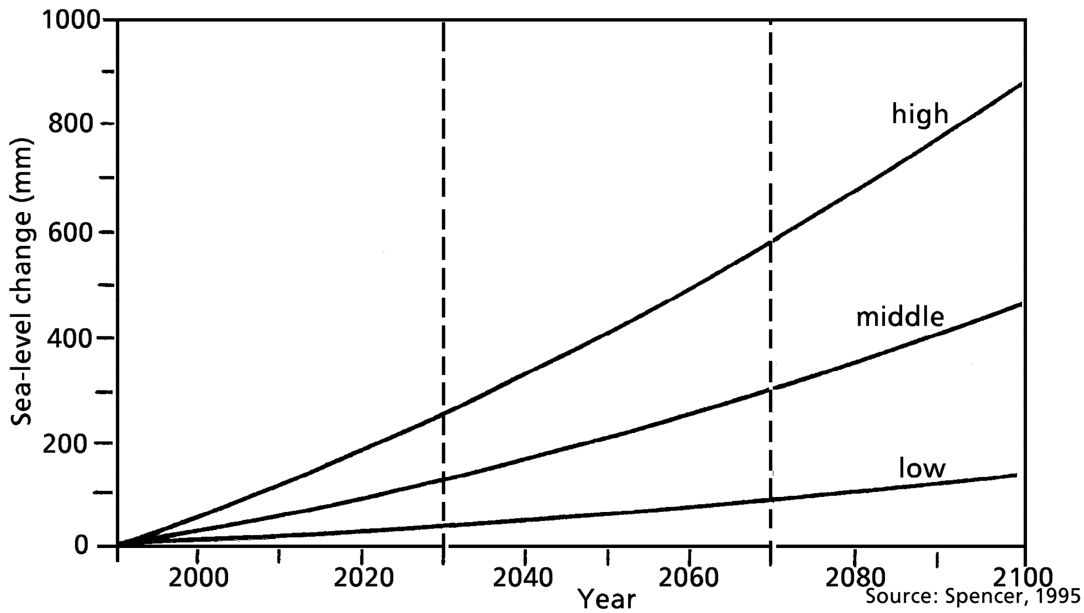

Figure 5. IPCC Projections for Sea Level Rise during the Next 100 years.

* Rhoads et. al (1987) estimated that approximately 1300 square miles of Everglades National Park lies below the one-foot contour. Their paper suggested that, within the next 20 years, an additional 5 to 6 percent of this land area may become inundated by sea water.

4.3 Hurricane Occurrence

* Prior to the early 1990s, the general consensus was that the occurrence of hurricane strikes had been on a declining trend since 1960s. An analysis of hurricane strikes in Florida over the last century showed a significant fluctuation with a general downward trend in recent years **(Figure 6).**

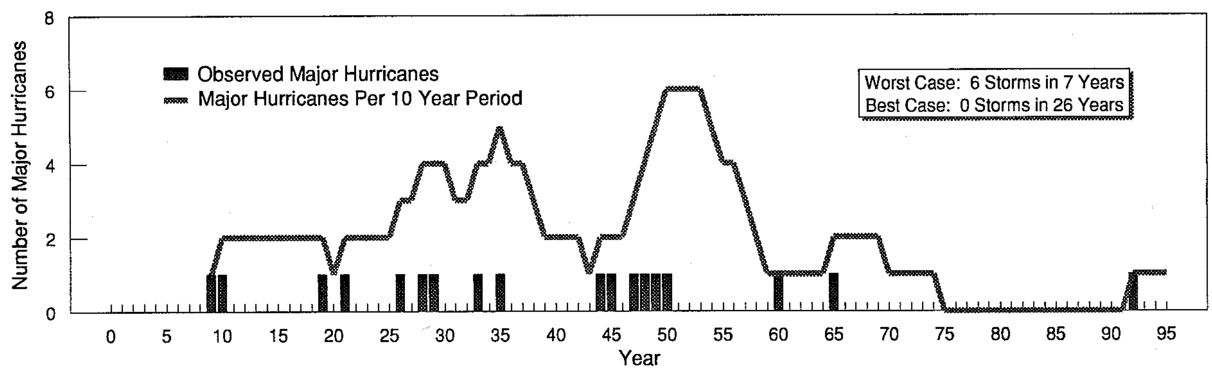

Figure 6. SFWMD Major Hurricane Strikes (CAT 3+) during this scentury (1900-1995).

* Gray (1990) linked hurricane activity to precipitation in the Western Sahel Region of West Africa **(Figure 7)** and suggested that the incidence of intense hurricanes making landfall on U.S. coast and in the Caribbean basin will likely increase during the 1990s and early years of the 21st century.

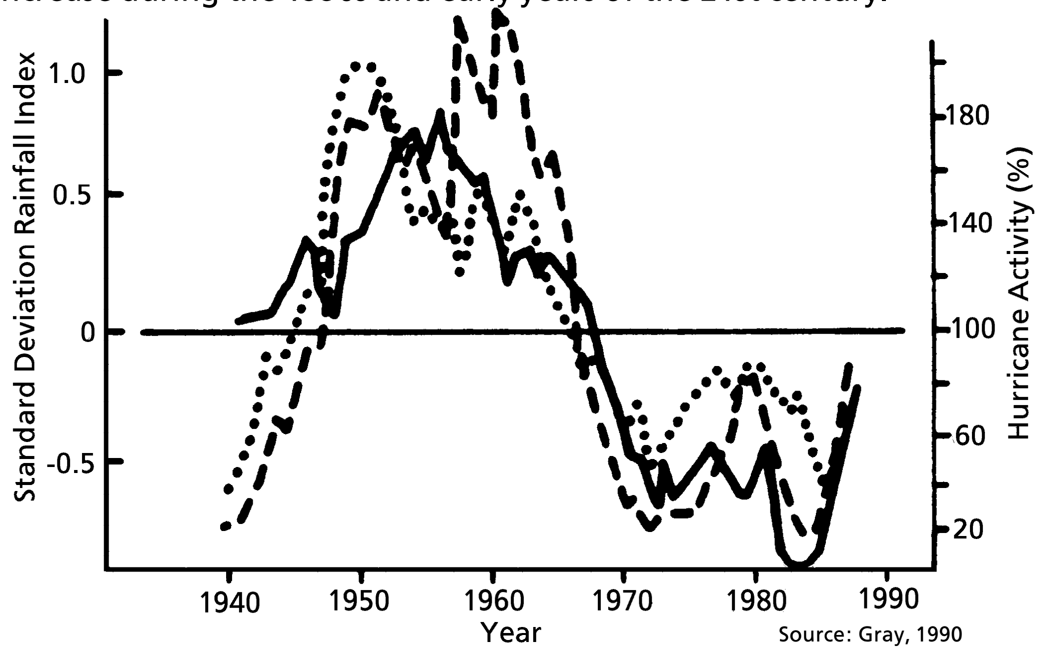

Figure 7. Comparison of 5-Year Running Averages for June through September Rainfall in the Western Sahel (solid line) versus Percent Probability of Category 3, 4 or 5 Hurricane (dashed lines) and of Category 3, 4 or 5 Hurricane Days (dotted lines).

* Gray also predicted that the Atlantic Ocean Conveyor Belt, which is a continuous, conveyorlike megacurrent that cycles water from the Indian and Pacific Oceans into the Atlantic and back, is poised to increase its pace. He believes that a slower conveyor belt during the last 25 years has coincided with more El Nino events, less rainfall in Africa, stronger zonal winds and sea

surface temperatures. These "proxy manifestations" of the conveyor belt variability have been linked to hurricane activity (EOS, 1995) .

4.4 Predictions from Global Climate Models (GCMs)

* Global Climate Models are the primary tools that have been applied to evaluate climate change. Most of the effort using GCMs in terms of climate change has concentrated on (i) the greenhouse warming effect; and (ii) the "nuclear winter" scenario (Pielke et. al, 1988).

* Pielke et al. (1988) summarized results of three different GCMs for a hypothetical scenario in which carbon dioxide concentrations in the atmosphere were doubled throughout the world. The results indicated that, in five out of six cases, a reduction of precipitation occurred in South Florida. An average prediction of 0.5 mm/day reduction of rainfall, if sustained throughout the year, corresponds to about 7 inches of moisture loss. This amounts to about a 15 percent decrease in district-wide average annual rainfall and a corresponding, probably greater, decrease in runoff. The results of GCMs however, should be used with extreme caution because of the very low resolution of these models at local scales (one or two cells in the model represent all of South Florida).

5. RECOMMENDATIONS

The following recommendations were developed by analyzing the information discussed in the previous sections.

Task 1. Investigate potential impacts of and develop solutions for sea level rise.

Subtask	Who	FTE	$	FY	Priority
a. Continue to monitor Intergovernmental Panel on Climate Change (IPCC) activities to determine the probable range of sea level rise and associated probabilities.	*SFWMD*	*0.1*	10K	*1997*	*High*
b. Select and apply an existing Density-Dependent Ground Water/Surface Water Model to an area in Lower east Coast Planning Area to investigate impacts of sea level rise.	*SFWMD/ Contract*	*0.1*	*75K*	*1997*	*High*
c. Determine potential flooding impacts of various sea level rise projections and develop solutions to minimize or account for these impacts.	*SFWMD/ Contract*	*0.1*	*25K*	*1997*	*High*

Task 2. *Perform a thorough analysis of historical and other climatic data for South Florida and elsewhere to determine the presence or absence of trends that should be considered and incorporated into decisions regarding operation of the C & SF system.*

Subtask	Who	FTE	$	FY	Priority
a. Complete trend analyses of South Florida Rainfall	*SFWMD*	*0.25*		*1997*	*High*
b. Assemble and analyze historical data sets of other climatic variables	*Contract*		*50K*	*1998*	*Medium*
c. Develop and analyze long-term rainfall records from paleological information	*Contract*		*25K*	*1998*	*Low*
d. Develop empirical models for short and long-term forecasting of rainfall, water supply and hurricane conditions.	*Contract*		*75K*	*19 98*	*High*
e. Develop methods to incorporate rainfall forecasts into current operations	SFWMD	0.25		1997	High
f. Develop methods to incorporate short-term rain-fall forecasts into development of regulation schedules, rain driven operational procedures, etc.	Contract		50K	1998	High

Task 3. Incorporate multiseasonal (10-20 year) hurricane frequency forecasts in making management decisions regarding OMD resources and functions.

Subtask	Who	FTE	$	FY	Priority
a. Improve Emergency preparedness procedures	SFWMD	0.10		1997	Ongoing
b. Evaluate personnel and equipment requirements	SFWMD	0.10		1997	Ongoing

Task 4. Link the District's hydrological models to Mesoscale Climate Models developed by other agencies and investigate the impacts of land use changes on the local climate.

Subtask	Who	FTE	$	FY	Priority
a. Obtain services of a contractor (expert asssist.) and conduct a feasibility investigation for dynamic environmental effects monitoring	Contract		25 k	1997	High
b. Acquire and implement a suitable climate model	Contract		100 K	1998	Medium
c. Link the hydrology model using Dynamic Effects Environmental Model (DEEM) developed by Argonne National Laboratory	SFWMD/ Contract	0.50	100 K	1998	Medium
d. Conduct Scenario analysis	SFWMD	0.50		1998	Medium

Task 5. Monitor the state-of-the-art developments in Global Climate Change Programs and determine the potential consequences that should be considered in the management of water and environmental resources in South Florida.

Subtask	Who	FTE	$	FY	Priority
a. Monitor Global Climate Change programs	*SFWMD*	0.05		*19 97*	*Ongoing*
b. Develop procedures to incorporate findings of the Climate Change programs in water management activities	*SFWMD*	*0.10*		19998	*Ongoing*

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APPENDIX A

CAUSES OF CLIMATE & RELATED CHANGES AND THEIR IMPACTS

A.1 Natural Causes and Impacts

Sunspots Solar sunspots are generally darker, cooler spots on the sun. However, other disturbances associated with sunspots, such as solar flares and electromagnetic disturbances are also believed to contribute significantly to climate fluctuations. Regional climate fluctuations for several regions of the United States have been explained by solar sunspot cycles (Perry, 1990, 1995). For example, Paine (1983) explained how the 1981-1982 rainfall deficits over eastern United States could be associated with a solar sunspot maximum that occurred in late 1979.

Research to date suggests that the hydro-climatological responses lag the solar sunspot activity by a few years. If this is the case, there may be a potential for predicting climatic variations in particular regions where climate exhibit high correlation to sunspot cycles.

El Nino-Southern Oscillation The signature of an El Nino event is the occurrence of very warm ocean water at low latitudes off the west coast of South America. This region of the ocean normally has cooler waters. The Southern Oscillation Index (SOI) is the measure of sea level atmospheric pressure differences between Darwin (western Pacific) and Tahiti (eastern Pacific) islands. There is a strong connection between the El Nino event and the Southern Oscillation Index. The El Nino-Southern Oscillation Event is often referred to by the acronym ENSO.

Climate events that occur within the state of Florida are strongly affected by ENSO events. Hanson and Maul (1991) identified a strong statistical relationship between Florida precipitation and the El Nino events. Several droughts and rainfall events appear to be closely related to ENSO events making it vital that water managers understand what effects these changes may have on the climate of Florida.

Volcanic Activity The volcanic activity has more significant effects when this activity occurs near the equatorial convergence zone. Volcanic particulate matter may be lifted to great heights and mixed thorough large regions by the atmosphere's mean circulation pattern. A general cooling of the earth's atmosphere occurs as the particulate matter in the atmosphere blocks the incoming solar energy from reaching the earth's surface. In recent historical times, the largest such event was eruption of the Tambora volcano (Indonesia, 1815), which produced the notable "year without a summer" (Stommel and Stommel, 1983).

Atlantic Ocean Conveyor Belt The conveyorlike megacurrent that cycles water from the Indian and Pacific Oceans into the Atlantic and back - particularly warm water from the tropical Atlantic to the edge of the Arctic - is believed to be the driving force behind the cyclical, decades-long trends in sea surface temperatures. These pattern, in turn, affect the multidecadal storm patterns. William Gray, the noted scientist who predicts Atlantic hurricane activity, believes that the conveyor belt has been slowed down for 25 years. This change has coincided with more El Nino events, less rainfall in Africa, and stronger zonal winds. Gray suggested that all these are "proxy manifestations" of the conveyor belt variability (EOS, 1995).

A.2 Man-Made or Man-Induced Changes and Impact

A.2.1 Local

Large scale changes in water management. Previous investigations have hinted that the drainage of large scale wetlands can have a major impact on summer convective rainfall over south Florida. Art Marshall (reported by Boyle and Meachem, 1982) suggested that the 1981 drought was not a "meteorological aberration but a predictable of consequence of the land development and the drainage of wetlands in the Everglades and Kissimmee River basin that have disrupted the normal rainfall cycle." His theory suggested that recent land development activities have reduced the amount of sheetflow. The consequently reduced rate of evapotranspiration is insufficient to initiate what is called the "rain machine."

Since south Florida naturally has considerable standing water and wet peat soils, the elimination of these areas is likely to have deleterious effects on precipitation, and may result in higher surface temperatures (Pielke, 1988). These higher temperatures will further dry out the soils through enhanced evaporation and evapotranspiration.

Urbanization Changes in land use through urbanization are known to influence the fluxes of heat and moisture into the atmosphere. Past and future urbanization along the east coast of South Florida may further alter the precipitation pattern. The slowly-developing, spatially uniform, precipitation pattern that is thought ot have occurred historically may change to one with more spatial deviation and larger high intensity events

A.2.2 Global

Greenhouse Warming Due to Greenhouse Gases The greenhouse effect is caused by gases in the atmosphere which allow the short-wave solar radiation to pass directly through the atmosphere and be absorbed by the earth's surface. These same gases, however, reduce the amount of long-wave terrestrial radiation that occurs from the earth's surface through the atmosphere to outer space. Instead, this energy is absorbed by the greenhouse gases, which re-radiate a portion of the energy back towards the earth. This is similar to the process that warms the environment in a greenhouse. The glass allows sun rays into the greenhouse but does not allow sensible heat to escape through the glass.

Greenhouse gases include carbon dioxide (CO_2) and methane (CH_4) which are strong absorbers of infrared radiation. If man produces more greenhouse gases than would occur naturally, or removes photosynthetic biomass which normally provide a natural sink of these gases, the net result may be a warming of the lower troposphere. In recent years, an increase in the combustion of fossil fuels due to industrialization has led to a significant build-up of greenhouse gases in the atmosphere. Global warming is predicted to be in the range of 2 to 5 degrees Celsius over next 100 years,

Preliminary results reported by Pielke et. al (1988) indicate that south Florida may be a warmer and drier place to reside if the carbon dioxide concentration in the atmosphere doubles. These results should alert water resource managers and planners that water management planning efforts need to consider a wider range of climatic conditions that may exist in the future.

Sea-Level Rise A consequence of global warming is a global sea level rise through oceanic thermal expansion and enhanced melting of alpine and continental glaciers. The exact magnitude and rate of the expected sea level rise, however, has been, or continue to be, fraught with uncertainties. The "best guess" estimate offered in 1992 by the Intergovernmental Panel on Climate Change (IPCC) was 48 cm (1.6 ft.) by the year 2100.

The consequences of sea level rise attributable to global warming include the following:

(a) Inundation of low lying coastal areas. This is the most obvious impact of sea level rise. It has both a permanent component, resulting in land loss, and a recurring element, due to storm-induced flooding. Endangered or threatened species would be adversely impacted by an increased sea level if the coastal habitats critical for their survival become unsuitable.

(b) Salt Water Intrusion. Sea level rise would generally enable salt water to advance inland in both aquifers and estuaries. Water depth increases could also lead to changes in tidal ranges and currents in bays and estuaries which could further alter salinity conditions (ASCE Task Committee, 1993). The potential impacts of sea level rise on Florida's Everglades and shallow aquifers around Miami might be significant, but these have not been investigated (Titus, 1989).

(c) Erosion. Coastal marsh systems may also be negatively affected by increased shoreline erosion accompanying sea level rise. Higher sea levels may result in coastal recession because the waterline will naturally shift landward due to submergence. Coastal natural communities may be eliminated if they "run out of room" to expand inland due to the presence of seawall or other man-made (or natural) protective barrier.

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APPENDIX B - SENSITIVITY OF WATER MANAGEMENT MODELING RESULTS TO CLIMATE CHANGES THAT AFFECT DISTRICT-WIDE RAINFALL

The ability to meet water management objectives if a shift of climate occurred which produces either lesser or greater amounts of rainfall is tested with the application of the South Florida Water Management Model (SFWMM). This application of the model only considers the direct changes in rainfall and not likely increases (decreases) of evapotranspiration that would be associated with lower (higher) humidity and higher (lower) solar insolation that would likely occur with a shift to a drier (wetter) climate. This sensitivity analysis was comducted by increasing and decreasing rainfall by 10 percent for the historical rainfall conditions that occurred for the period of 1965 through 1990. The ability to meet the water management objectives for each case is accomplished by comparing key computed performance measures of each scenario to that which no rainfall adjustment is made to the historical rainfall.

B.1 Model Runs. A total of three model runs were made to investigate the effect of 10 peracent increase and decrease in rainfall. They are as follows:

CB2.7 This is the base conditions with 1990 land use and current operational procedures assumed to be valid over the entire period of simulation which is 1965 to 1990.

RF_M10 This is same as CB2.7 except the rainfall over the model domain is decreased by 10 percent.

RF_P10 This is same as CB2.7 except the rainfall over the model domain is increased by 10 percent.

B.2 Lake Okeechobee Water Levels. Figures A-1 and A-2 illustrate the effect on Lake Okeechobee water levels of the variation of rainfall. It is clear from these figures that the Lake Okeechobee level is sensitive to the rainfall decrease particularly during major droughts. The effect of lesser rainfall is minimized by supply side management cutbacks in water use while the effects of increased rainfall are limited by regulatory discharges to the ocean for the sake of flood protection. These strategies are not without a cost.

B.3 Economic Losses and Discharges to Estuaries. Figure A-3 illustrates that the Everglades Agricultural Area economic losses increases by more than 4 times, from 22 million dollars to 96 million dollars for the period, with a ten percent decrease in rainfall. Likewise, **Figures A-4 and A-5**illustrate the increase in the number of days of large discharges to the St. Lucie and Caloosahatchee estuaries with a ten percent increase in rainfall.

B.4 Lower East Coast Urban Area Wellfield Cutbacks Figure A-6 illustrates the sensitivity to cutback volumes of decreasing and increasing the rainfall by 10 percent, while **Figure A-7** converts the cutback volumes to economical impacts.

B.5 Effects on Everglades National Park. Finally, **Figure A-8** illustrates the change in the average monthly flows to Everglades National Park due to a ten percent increase or decrease of rainfall. **Figure A-8** also includes the simulated natural system water levels (estimated with the Natural System Model version 4.2) estimated with no adjustment to the water levels. These graphics of key performance measures illustrate that even a relatively small change in rainfall totals can have large impacts in rainfall.

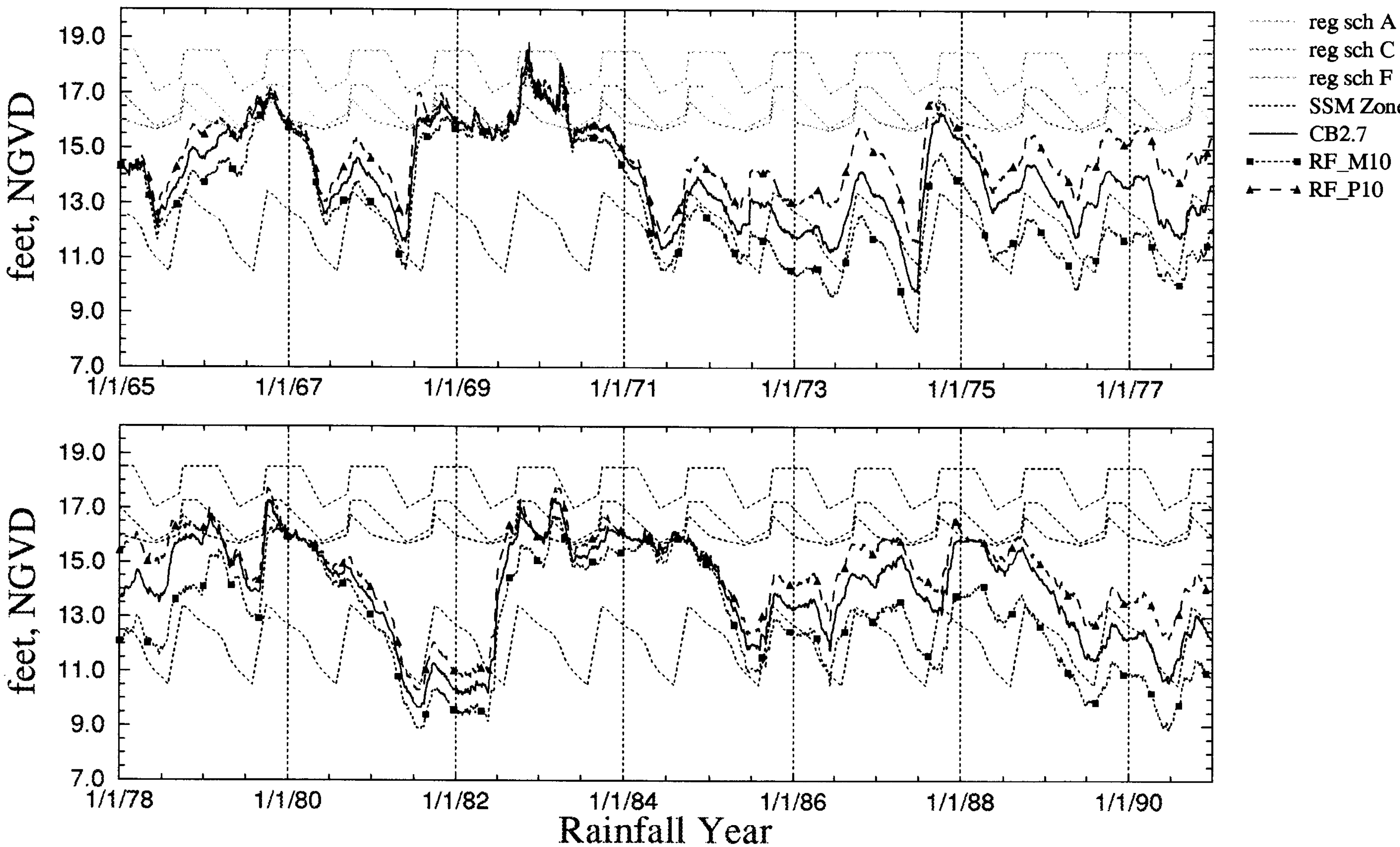


Figure B-1 - Effect of the variation of rainfall on Lake Okeechobee daily stage hydrographs

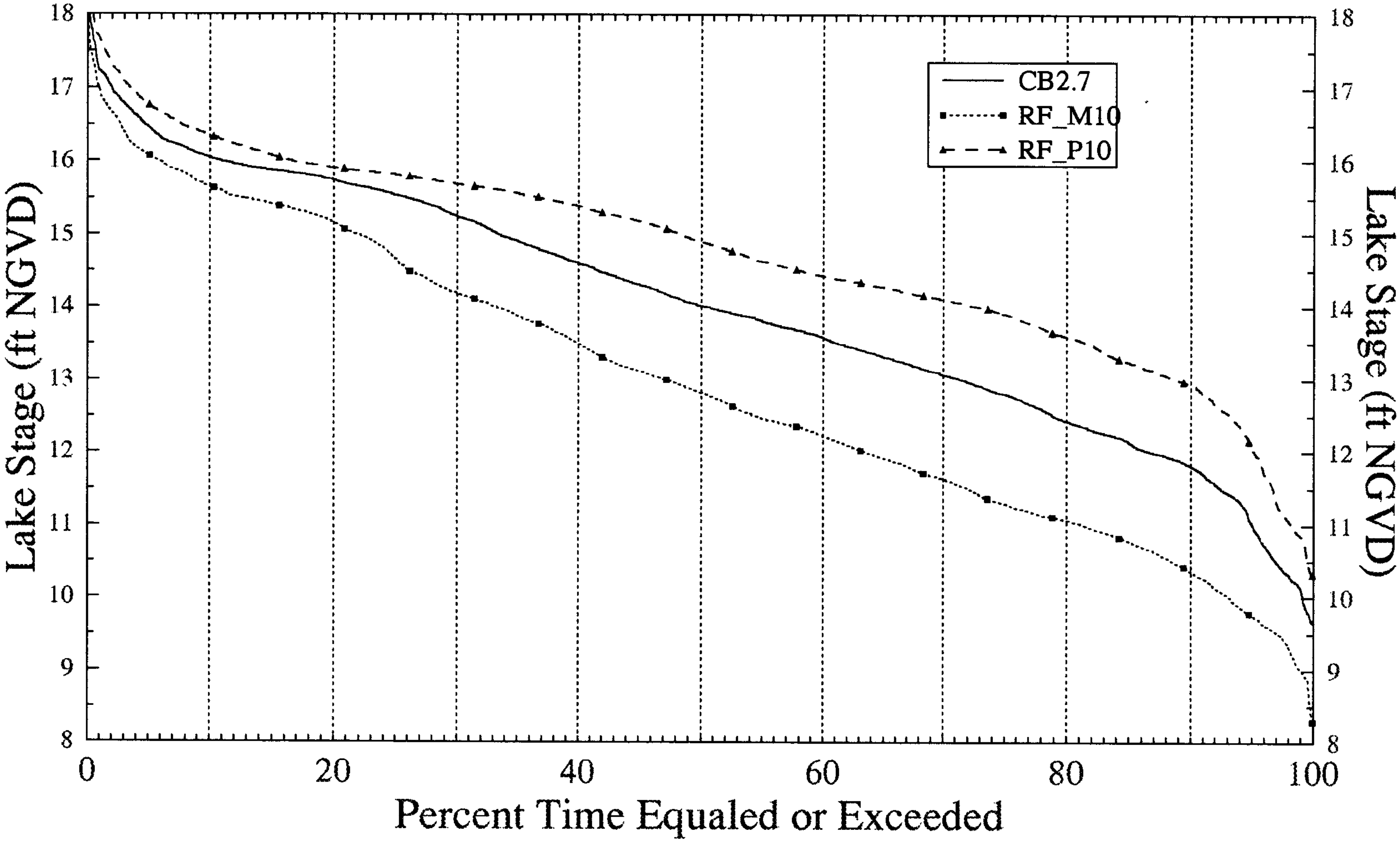
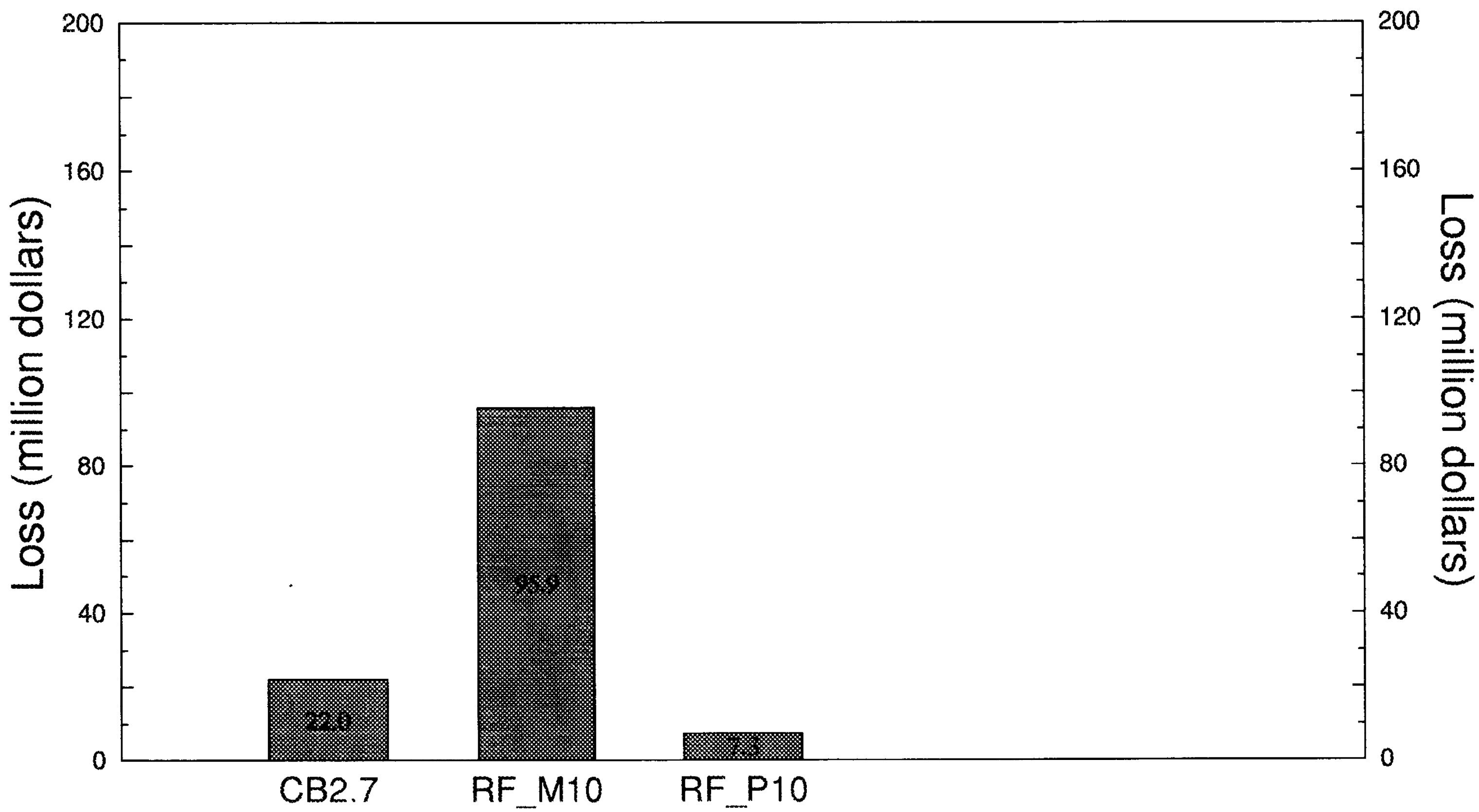
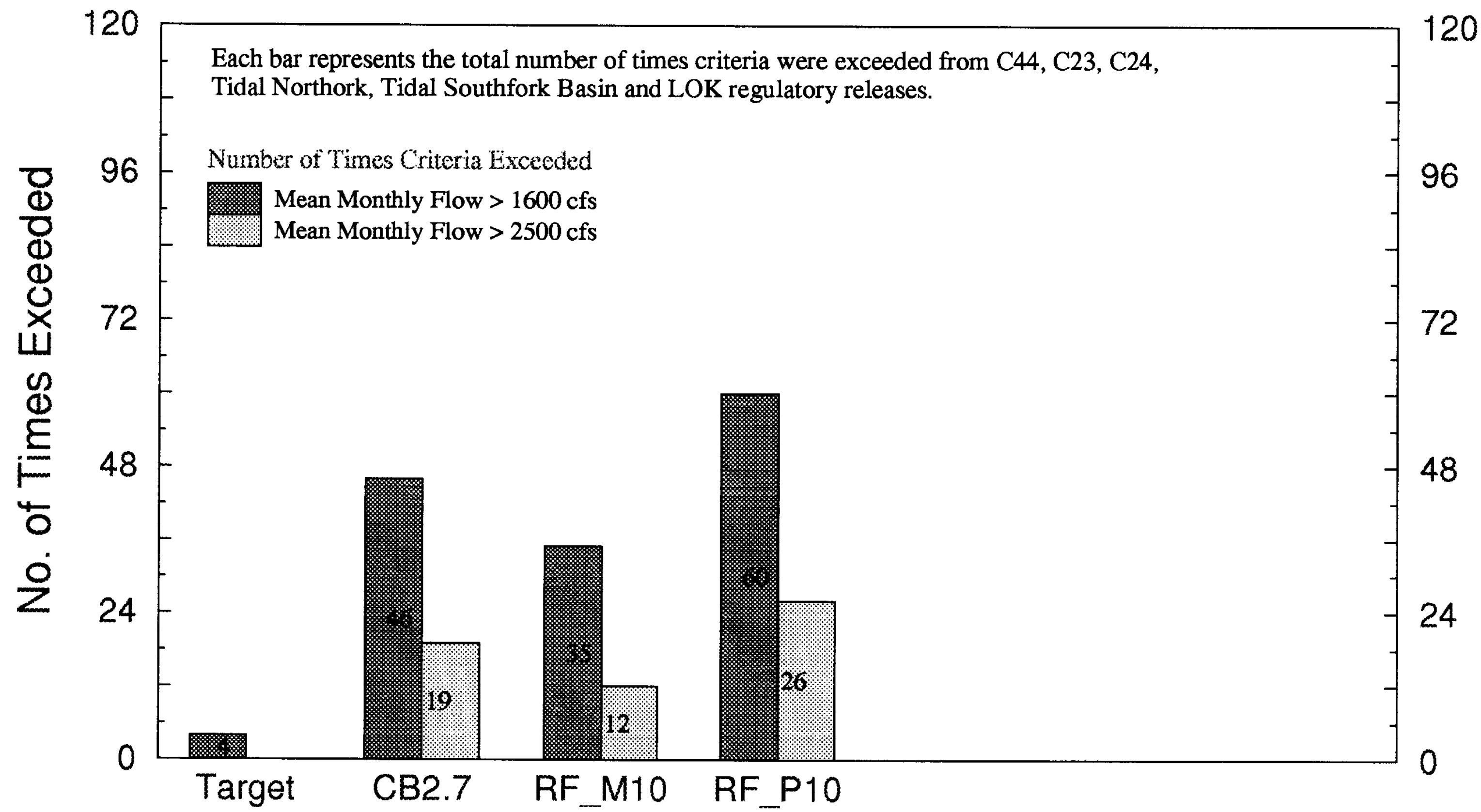


Figure B-2 - Effect of the variation of rainfall on Lake Okeechobee stage duration curves



Note: Losses are based on Yield Reductions for Sugarcane in the EAA.
Sugarcane acreage(acres): 529,920(1990) 491,520(2010)

Figure B-3 - Everglades Agricultural Area economic losses increases by more than 4 times, from 22 million dollars to 96 million dollars for the period, with a ten percent decrease in rainfall



Note: A favorable maximum monthly flow was developed for the estuary (1600 cfs) that will theoretically provide suitable salinity conditions which promote the development of important benthic communities (eg. oysters & shoalgrass). Mean monthly flows above 2500 cfs result in freshwater conditions throughout the entire estuary causing severe impacts to estuarine biota.

Figure B-4 - Number of days of large discharges to the St. Lucie Estuary with a ten percent increase in rainfall

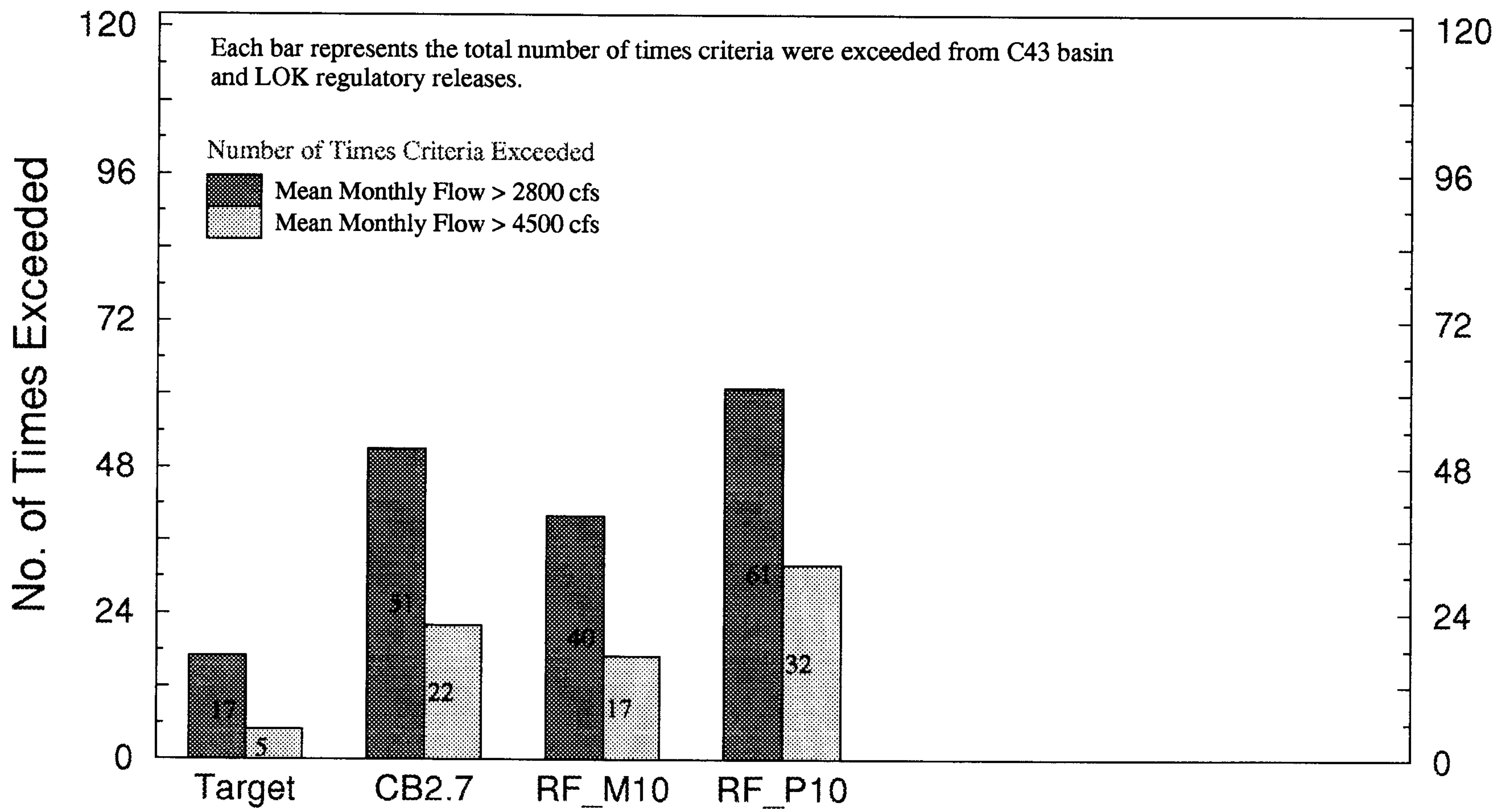


Figure B-5 - Number of days of large discharges to the Caloosahatchee estuary with a ten percent increase in rainfall

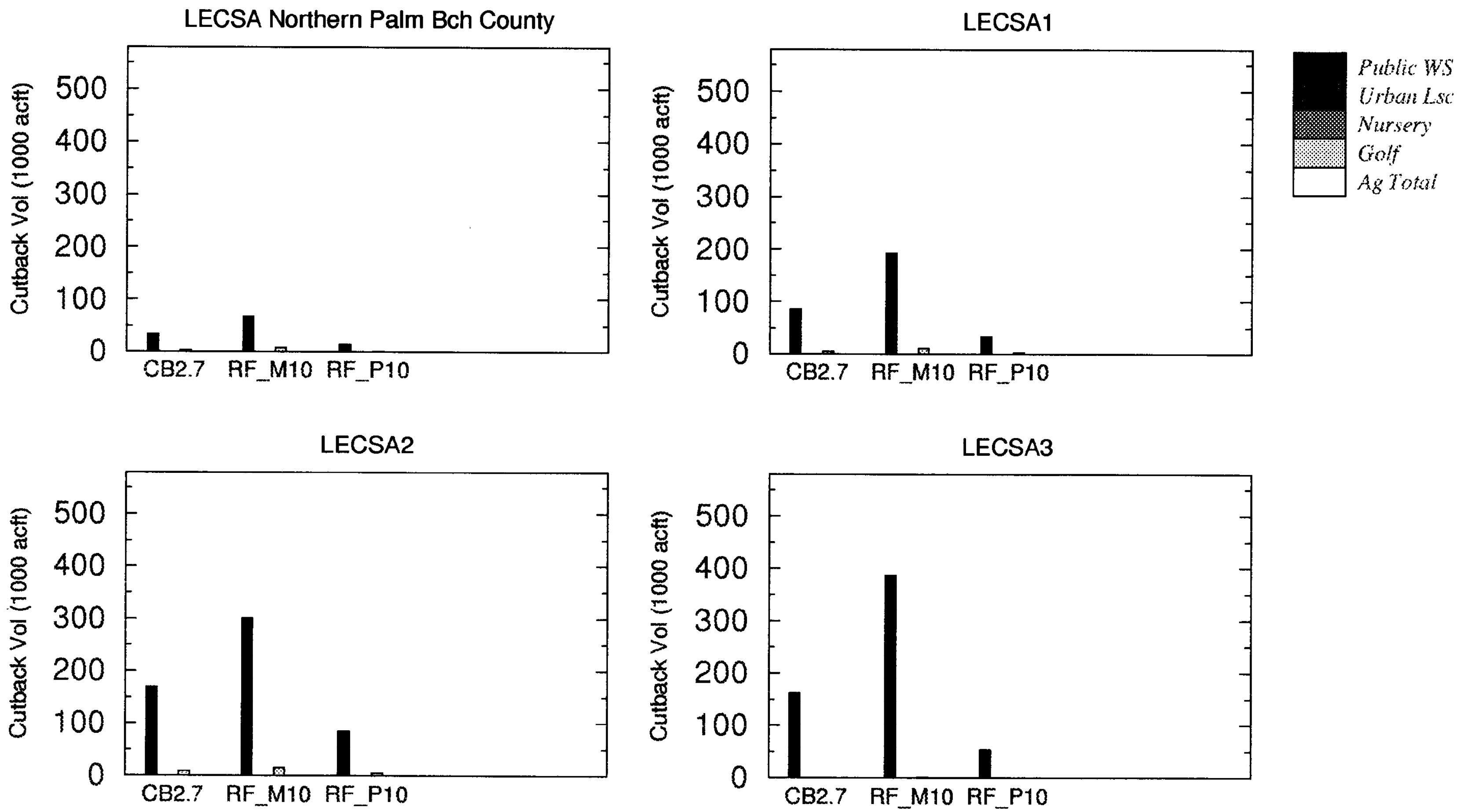


Figure B-6 - Sensitivity to cutback volumes of decreasing and increasing the rainfall by 10 percent

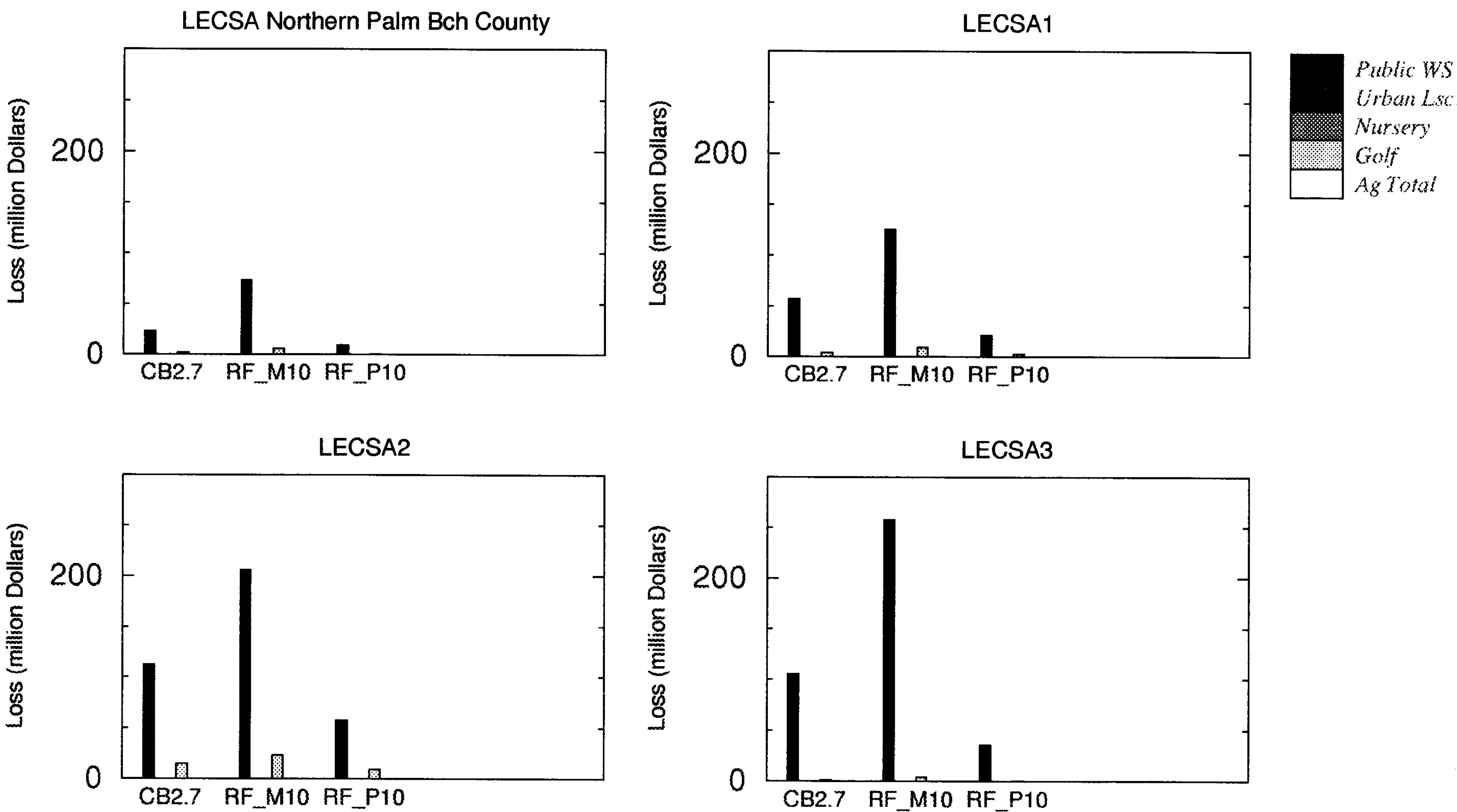


Figure B-7. - Cutback volumes converted to economical impacts

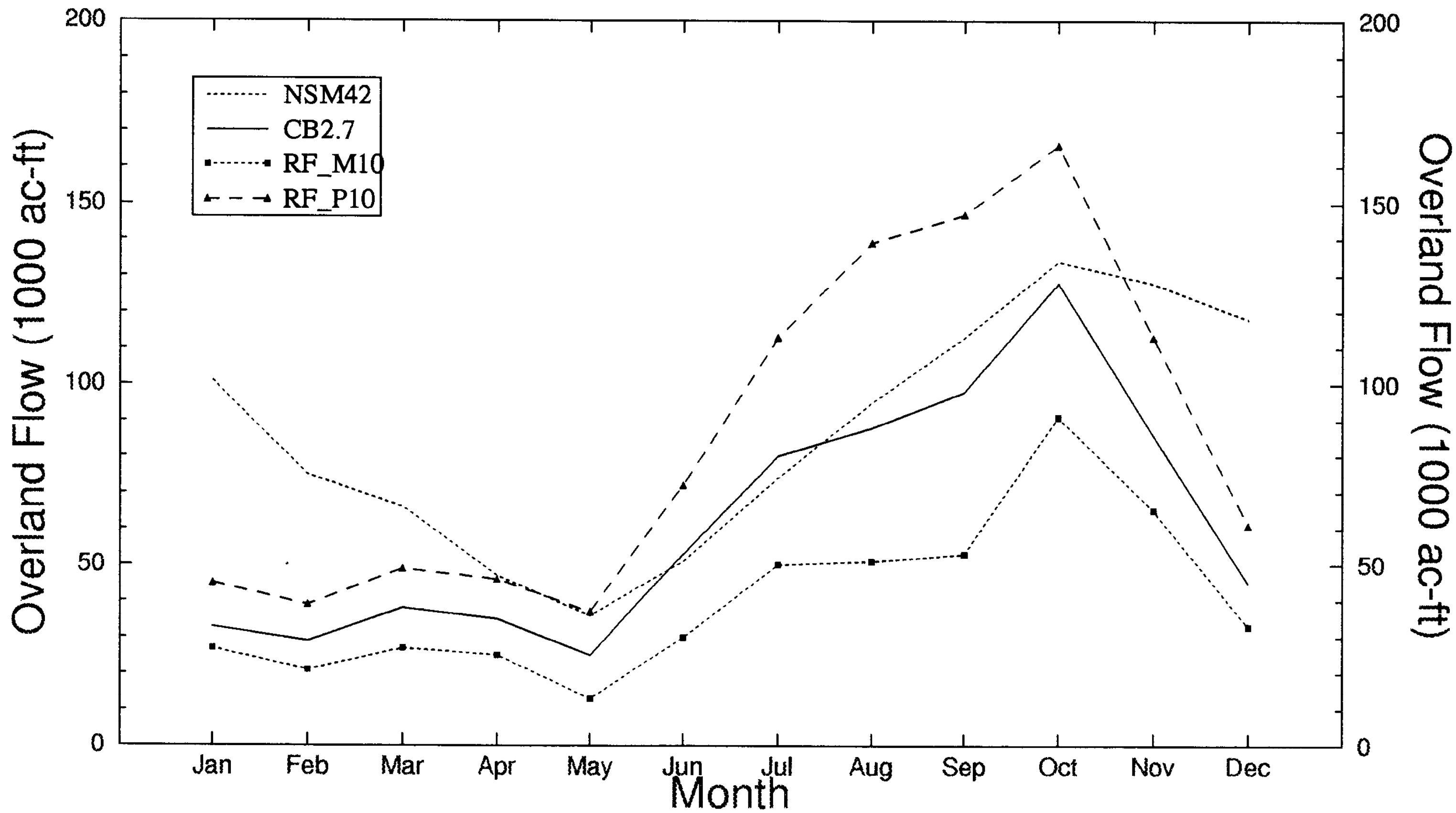


Figure B-8. - Change in the average monthly flows to Everglades National Park due to a ten percent increase (RF_P10) or decrease (RF_M10) of rainfall